Debuncher and Accumulator Beam Abort Systems

Pre CD-1 Director's Design Review
05/03/2011

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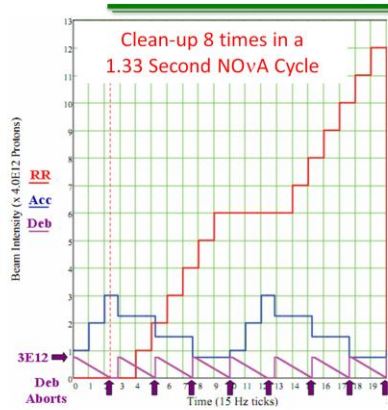
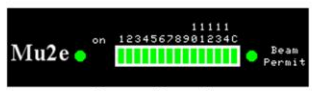
Abort System Requirements

For both the Debuncher and Accumulator Aborts, we must define:

- Beam Intensity Requirements
  - "Clean-up" of leftover beam each cycle.
  - Beam Permit Drops
- Abort Line Design Requirements
  - Location
  - Abort Line
  - Dump Design
- Beam Dump Radiation Safety Requirements
  - Ground Water
  - Surface Water
  - Air Activation
  - Residual Radiation
- Beam Dump Mechanical Requirements
  - Thermal cooling

Debuncher Abort: Beam Being Sent to the Abort





Beam Permit

- **Clean-up Leftover Beam**
  1. In a 1.33 second Nova cycle, there are eight iterations of 3.0×10^{12} 8GeV protons being injected into the Debuncher and resonantly extracted to the Mu2e experiment.
  2. It is assumed that 95-98% of the beam will be successfully spilled each cycle
  3. The remaining 2-5% of the beam (5% would be 9.0×10^{11} protons/sec) needs to be sent to a beam abort.
- **Beam Permit Trips**
  1. There is a finite amount of time needed to reset an abort trip.
  2. Experience with Booster and MiniBooNE shows us that we would never expect more than one permit trip per minute.
  3. In this case the abort would need to be able to take the entire injected Debuncher beam intensity (3.0×10^{12}).
  4. 3.0×10^{12} protons/minute or 5×10^{10} protons/sec.

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3×10^{12} protons/Deb cycle = (4×10^{12} protons/Booster batch) x (1 batches/Acc cycle) X (3 Acc cycles/4 Deb cycles)

9×10^{11} protons/sec = [(6 Booster batches) x (4×10^{12} protons/pulse) x (0.05)]/1.33 seconds

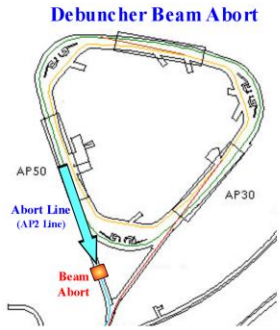
5×10^{10} protons/sec = (3×10^{12} protons/minute)/(60 sec/min)

Debuncher Abort: Beam Intensity Requirements

- Per Pulse Rate
  - 3.0 x 10^{12} protons/pulse
- Expected Rate (clean-up + permit trips + 50% safety margin)
  - 1.5 x 10^{12} protons/sec
- Power Transmitted to Dump
  - 1.92 KW
- Sustained rate (80% uptime)
  - 3.78 x 10^{19} protons/year.

$3x10^{12}$ protons/Deb cycle = ($4x10^{12}$ protons/Booster batch) x (1 batches/Acc cycle) X (3 Acc cycles/4 Deb cycles)
$1.5x10^{12}$ protons/sec = 1.58 x ($9.0x10^{11}$ protons/sec cleanup + $5.0x10^{10}$ protons/sec abort)
1.92KW = (1.5 x 10^{12} protons/sec) x (8.0 x 10^{9} eV) x (1.60 x 10^{-19} J/eV) x (1 KW/1000 W)
$3.78x10^{19}$ protons/yr = ($1.5x10^{12}$ protons/sec) x (31,556,926 sec/yr) x 0.8

Debuncher Beam Abort: Choosing a Location



- Use the existing AP-2 line for the Debuncher Beam Abort
  - Locating abort dump in existing enclosure saves on civil construction costs.
  - The AP-2 line is not used for Mu2e.
  - The AP-2 line connects to the Debuncher in the correct direction to abort circulating Mu2e Debuncher beam.

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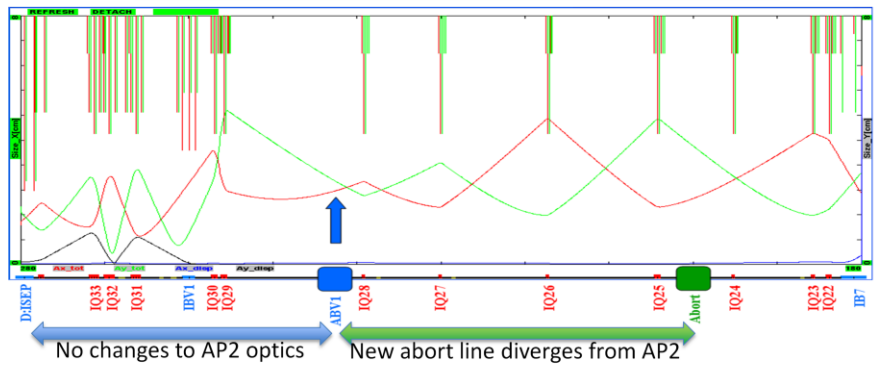
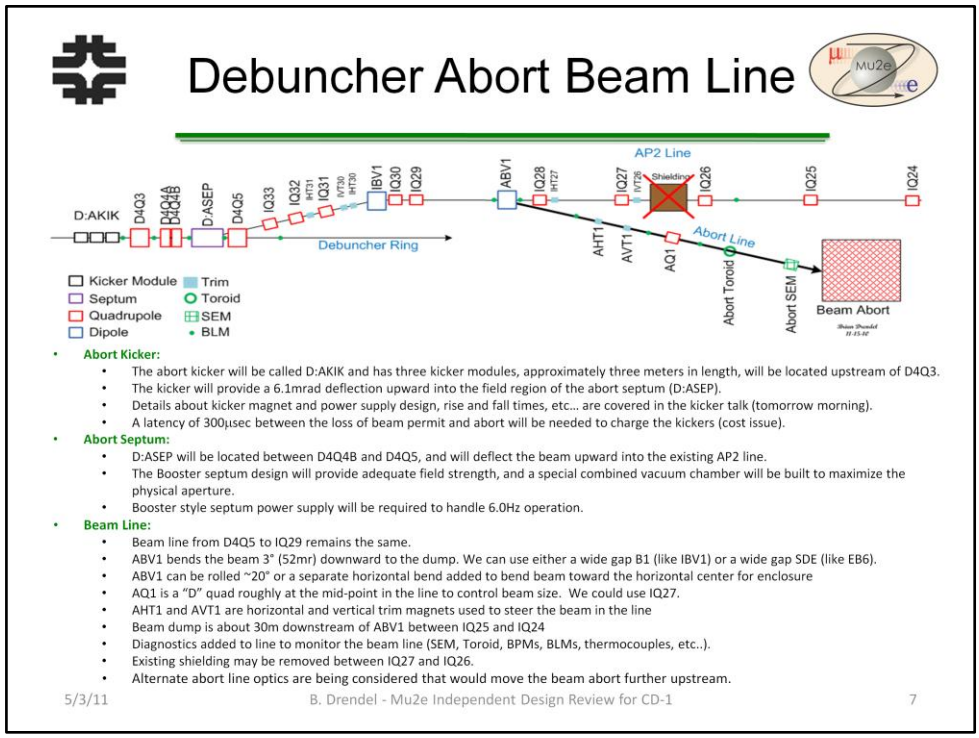
- Straight sections:
  - Under the service buildings – had less radiation shielding.
  - Highly populated.
- Free space in arcs between the service buildings are limited.

Debuncher Abort: AP-2 Line Optics

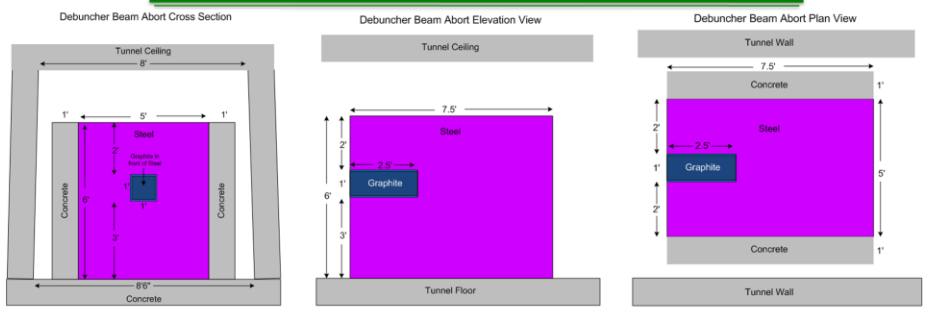


- Keeping optics the same at the beginning of the line avoids power supply or magnet changes.
- First 10m is located under or near the AP50 service building.
- First 40m of the line is very congested.
- Leave the beam line in tact from the Debuncher to IQ29.
- The beam line that spans IQ24 to IQ29 has lots of open areas for abort line and dump.



- D:AKIK
  - The abort kicker will be called D:AKIK and has three kicker modules, approximately three meters in length, will be located upstream of D4Q3.
  - The kicker will provide a 6.1mrad deflection upward into the field region of the abort septum (D:ASEP).
  - The Debuncher will have a single short 200nsec 2.5Mhz bunch, so kicker rise and fall times are not as restrictive as other Mu2e kickers.
  - Rise time will be 450nsec
  - Kicker will be synchronized to avoid the main bunch
  - Flat top time will be approximately 1,700 nsec to cover the entire revolution period of the Debuncher
  - Existing kicker magnets will be reused
  - Need to operate at 6Hz. Current power supplies cannot handle that, so a new power supply, controls and fluorinert cooling skid will be needed.
- D:ASEP
  - D:ASEP will be located between D4Q4B and D4Q5, and will deflect the beam upward into the existing AP2 line.
  - The Booster septum design will provide adequate field strength, and a special combined vacuum chamber will be built to maximize the physical aperture.
  - Booster style septum power supply will be required to handle 6.0Hz operation.
- Beam lines
  - Beam line from D4Q5 to IQ29 remains the same.
  - ABV1 bends the beam 3° (52mr) downward to the dump. We can use either a wide gap B1 (like IBV1) or a wide gap SDE (like EB6).
  - ABV1 can be rolled ~20° or a separate horizontal bend added to bend beam toward the horizontal center for enclosure
  - AQ1 is a "D" quad roughly at the mid-point in the line to control beam size. We could use IQ27.
  - AHT1 and AVT1 are horizontal and vertical trim magnets used to steer the beam in the line
  - Beam dump is about 30m downstream of ABV1 between IQ25 and IQ24
  - Diagnostics added to line to monitor the beam line (SEM, Toroid, BPMs, BLMs, thermocouples, etc..).
  - Existing shielding may be removed between IQ27 and IQ26.
  - Alternate abort line optics are being considered that would move the beam abort further upstream.

Debuncher Beam Dump in AP2: Initial Design



- Dump is a graphite core surrounded by iron and concrete centered in the enclosure.
- Dump is 6' tall x 7' wide x 7.5' long.
- Core is 1' tall x1' wide by 2.6' long and is located 3.5' above floor level.
- Drawing by Brian Drendel based on Mars model created by Igor Rakhno.

Steel

332 ft3

81.3 tons

Graphite

50,000 cc

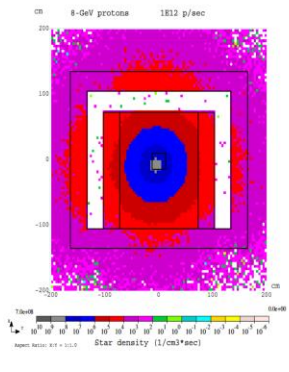
110 Kg

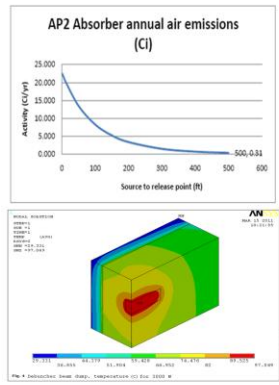
Concrete

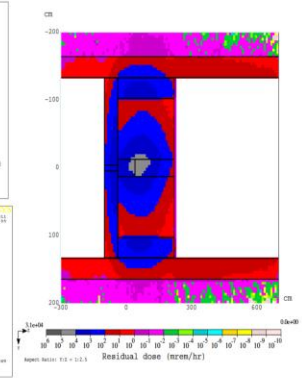
305 ft3

44.153 lbs

Debuncher Abort: Mechanical and Radiation Analysis







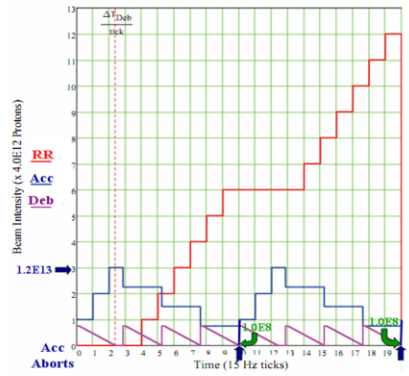
- MARS and ANSYS analysis were completed on our dump design at the expected beam intensities to check residual radiation, ground water, surface water and air activation, and thermal properties of the dump.
- Details are provided in supplemental slides at the end of this talk
- A summary of the results are presented on the next slide.

Debuncher Abort: Mechanical and Radiation Analysis

- Analysis results for Debuncher Beam Abort Located in the AP2 Line:
  - Surface Water (Kamran Vaziri)
    - Assumed 3.55 x 10^{19} protons/year
    - Conservative estimate of one sump discharge per month
    - Concentration of radioactive contaminants in the sump will be ~3% of the limits for surface water.
  - Ground Water (Kamran Vaziri)
    - Used the most conservative hydraulic conductivity in the vicinity of the AP-2 line.
    - After five years of operation, the concentration of radionuclides in the ground water will be 0.009% of the limit for ground water.
  - Air Activation (Kamran Vaziri)
    - Worst case scenario is about 23 Ci/year, which is about 50% of the current Pbar activation.
    - Overall Mu2e airflow plan will determine the exact numbers.
  - Residual Radiation (Igor Rakhno)
    - With additional shielding added on all sides of original design, the abort fills up the tunnel enclosure.
    - For an irradiation period of 30 days with a 1-day cool down, the residual dose rate is about 120mrem/hr at 30cm (can add more shielding or more cool down time).
  - Thermal Heating (Zhijing Tang)
    - Analysis shows that the dump will not require water cooling.

Accumulator Abort: Beam Being Sent to the Abort

- **Clean-up Leftover Beam**
  - The leftover Accumulator beam will be cleaned-up twice every 1.33 second Nova cycle.
  - **Intensity Per Pulse:** Approximately 1.0eE8 8GeV protons will be leftover every pulse.
  - **Average Rate** assuming 75% uptime:
    - 9.72 x10^{12} protons/day or 3.55 x 10^{15} protons/year
- **Beam Permit Trips**
  - **Peak Rate:** Over short periods the worst case scenario would have the permit dropping once per minute and would need to be able to handle the full intensity of all three booster batches injected.
    - 2 x 10^{11} protons/sec
  - **Average Rate:** Over the course of a day we would expect permit trips on the order of 10-100 times. For a day with 100 trips with 75% uptime
    - 9.0 x 10^{14} protons/day or 3.29 x 10^{17} protons/year.



Beam Permit

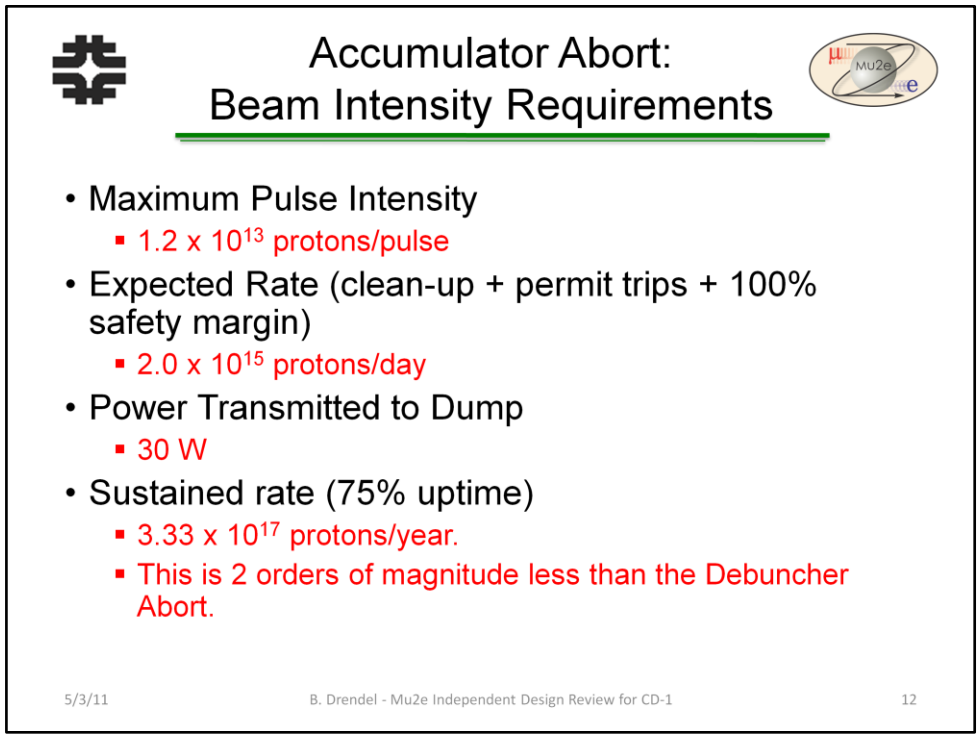
1.13 x10^{8} protons/sec = (1.0x10^{8} protons/Acc cycle) x (2 Acc cycles/Nova Cycle) x (1 Nova cycle/1.33 sec) x 0.75

9.72 x10^{12} protons/day = (1.13 x10^{8} protons/sec) x (86,400 seconds/day)

3.55 x10^{15} protons/year = (9.72 x10^{12} protons/day) x (365 days/year)

Peak Rate: 3 * (4 x 10^{12} protons) / 60 seconds = 2 x 10^{11} protons/sec

Average Rate: 3 * (4 x 10^{12} protons) * 100 * 0.75 = 9.0 x 10^{14} protons/day or 3.29 x 10^{17} protons/year.



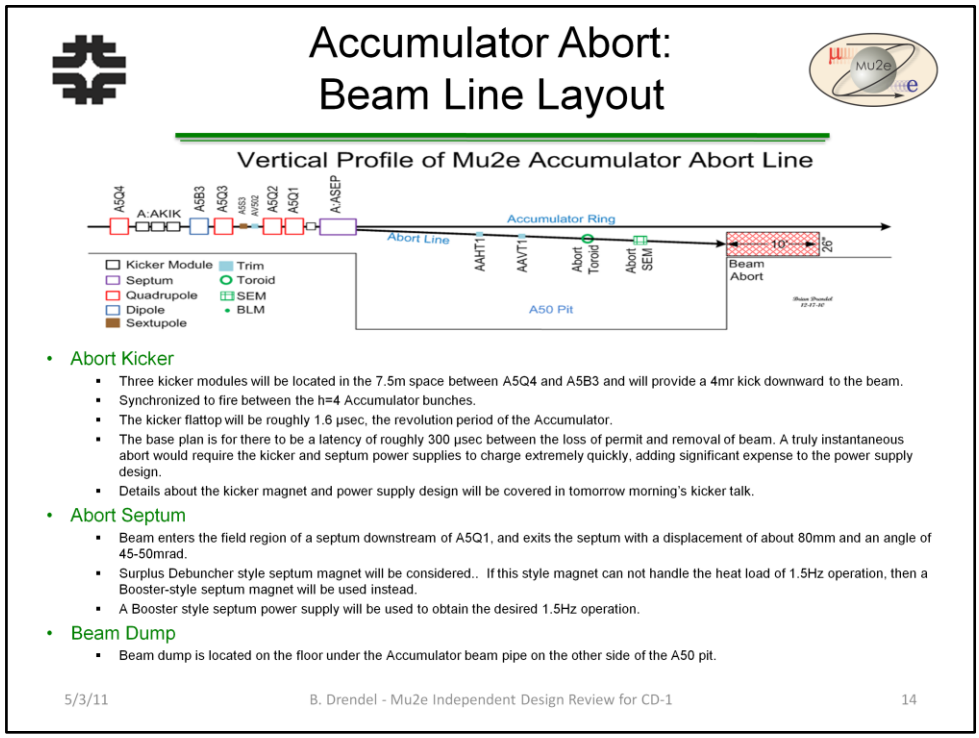
1.2×10^{13} protons = (3 Booster batches) x (4×10^{12} protons/batch)
2.0×10^{15} protons/day = [(9.72×10^{12} protons/day clean-up) + (9.0×10^{14} protons/day permit)] x (2.2 big safety margin)
30W = (2.0×10^{15} protons/day) x (1 day/86400 sec) x (8.0×10^{9} eV) x (1.60×10^{-19} J/eV)
3.33×10^{17} protons/year = [(3.29×10^{17} protons/year abort) + (3.55×10^{15} protons/year clean-up)]

Accumulator Beam Abort

The base plan is to place the Accumulator abort in AP50

- The Abort dump is located on the downstream side of the A50 pit, under the beam line.

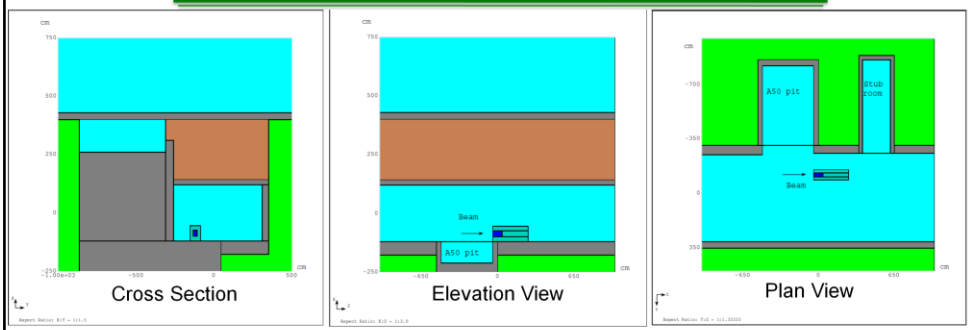
The abort could be placed in either in A30 or A50, but not A10 due to a space conflict with the Accumulator extraction septa.



In this scenario, a kicker and septum combination would both bend the beam down to a beam dump located near the A50 pit.

- Kicker
  - There is a period of vulnerability when the three injected Booster batches are momentum stacked, because the proton beam will be debunched. If the abort fires during this time, there will be beam loss from the kicker rising through some of the beam.
  - The kickers are expected to have a 150 nsec rise time, which will comfortably fit between bunched h = 4.
  - The kicker flattop will be roughly 1.6 µsec, the revolution period of the Accumulator.
  - The base plan is for there to be a latency of roughly 300 µsec between the loss of permit and removal of beam. A truly instantaneous abort would require the kicker and septum power supplies to charge extremely quickly, adding significant expense to the power supply design.

Accumulator Abort: Initial Design



- Dump is a graphite core surrounded by iron.
- Dump is 26” tall x 26” wide x 10’ long.
- Core is 10” tall x10” wide by 2.6’ long.
- Drawing from Mars model created by Igor Rakhno.

Steel

44.5 ft3

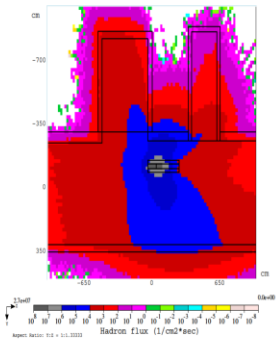
10.9 tons

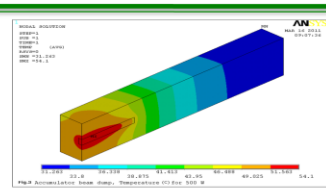
Graphite

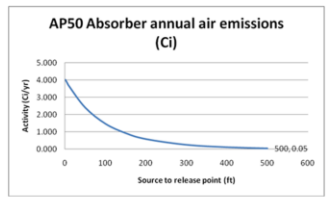
50,000 cc

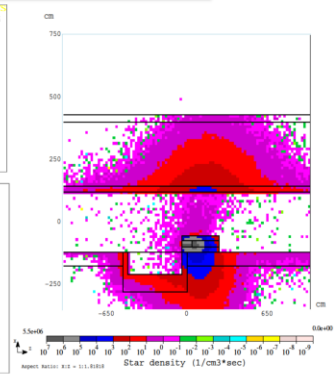
110 Kg

Accumulator Abort: Mechanical and Radiation Analysis









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- Details are provided in supplemental slides at the end of this talk
- A summary of the results are presented on the next slide.

Accumulator Abort: Mechanical & Radiation Safety Analysis

- Radiation Safety Analysis Results
  - Surface Water (Kamran Vaziri)
    - Concentration of radioactive contaminants in the sump will by 0.8% of the limits for surface water.
  - Ground Water (Kamran Vaziri)
    - After five years of operation, the concentration of radionuclides in the ground water will be 0.0002% of the limit for ground water.
  - Air Activation (Kamran Vaziri)
    - Worst case scenario is about 4 Curies per year, which is about 18% of release from the Debuncher beam dump.
  - Residual Radiation (Igor Rakhno)
    - For an irradiation period of 30 days with a 1-day cool down, the residual dose rate is less than the 100mrem/hr at 30cm limit.
  - Thermal Heating (Zhijing Tang)
    - Analysis shows that the dump will not require water cooling.

Summary

- Debuncher Beam Abort Design
  - The Debuncher beam abort will be located in the AP2 line.
  - Meets ground water, surface water and air activations limits.
  - Has acceptable residual radiation rates on both the upstream and downstream surfaces of the dump.
  - The thermal properties of the dump is sufficient to not require a water cooling system.
- Accumulator Beam Abort Design
  - The Accumulator abort will be located in the A50 straight section.
  - Meets ground water, surface water and air activations limits.
  - Has acceptable residual radiation rates at the dump.
  - The thermal properties of the dump is sufficient to not require a water cooling system.

References

- M. Syphers, Status of Mu2e Operating Scenario, Mu2e Document #787, February, 2010.
- I. Rakhno, Radiation Shielding of the beam absorber in the MI 8 GeV beam line, FERMILAB-TM-2340-AD, January 2006.
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- B. Pellico, Booster Beam Dump Justification, Internal Documentation, August 2006
- FESS Tunnel Drawings, Section 6.2.2, http://fess-oracle-web.fnal.gov:7778/gps/project_idx
- Technical Division, Accelerator Support Web, http://tdserver1.fnal.gov/AcceleratorSupport/index.html.
- I. Rahkno, K. Vaziri, Accumulator Beam Abort Mars Analysis, Mu2e Document Database #1498, April 2011.
- I. Rahkno, K. Vaziri, Debuncher Beam Abort Mars Analysis, Mu2e Document Database #1497, April 2011.
- Z. Tang, Temperature Analysis of the Mu2e Debuncher and Accumulator Aborts, Mu2e Document Database #1499, April, 2011.
- R. Schultz, Costing For Debuncher and Accumulator Abort, Mu2e Document Database #1494, April 2011.

Appendix

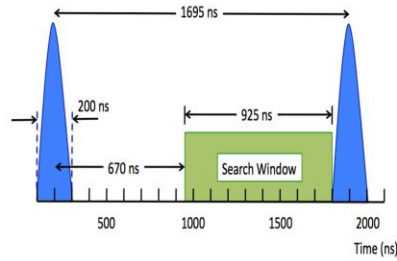
- Some extra slides not used in this talk

Debuncher Abort

- Supplemental Material for the Debuncher Abort Analysis

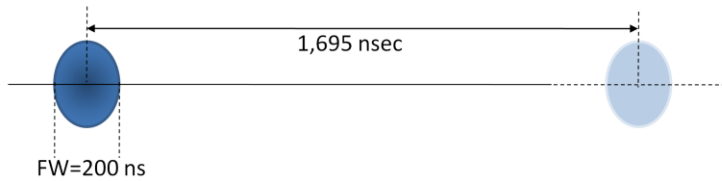
Debuncher Abort Kicker & Septum

- Debuncher Abort Kicker
  - Use the existing three D:IKIK kicker modules to provide 6.1mr kick needed to get into the field region of the injection septum
  - Beam is mostly contained in a single short 2.5MHz bunch, so a relatively slow 400nsec rise and fall time should be sufficient.
  - The flattop of the kicker needs to be at least 1.68 usec long to remove any beam that is not in the central bunch.
  - Kicker has to cycle at 7.5Hz.
  - "Accumulator and Debuncher Kickers" portion of this review has more details.



- Debuncher Abort Septum
  - Will need to operate at 7.5Hz.
  - Booster septum design will be used.

Debuncher Abort Kicker



- Bunches have 1,495 ns gap for the kicker to rise through
  - Shorter rise time OK if cost is not significantly increased
- Kicker flat-top needs to cover the entire revolution period of the Debuncher
  - Remove beam that has strayed out of bunch on normal cycles
  - Remove most of beam if it debunches
  - Kicker fires every Debuncher cycle to "clean-up" remaining beam

Debuncher Abort Kicker Requirements							
Integrated field (Kg-m)	Kick angle mrad	Rise time 95%/5% ns	Fall time 95%/5% ns	Flat top ns	Peak rate Hz	Average rate Hz	Duty cycle %
1.81	6.1	1,400	n/a	1,700	7.5	6.0	40

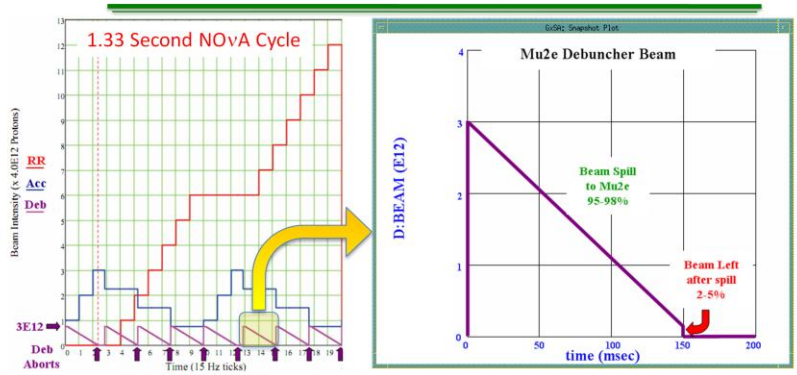
Debuncher Abort Kicker Plan

- Use existing Pbar Debuncher injection kickers at their present location
- Beam line layout (AP-2) and kicker field requirements remain the same
- Physical kicker aperture remains 42 mm horizontal x 56 mm vertical
- Power supply modeled after NOvA style kicker supply
- A single power supply with the three modules in series meets the rise time requirement
  - Magnet modules will need to be reconditioned
  - Power supply made up of one new switch tube, one new resonant charger, one new 10 Ω load, one new control system, one new Fluorinert cooling system

Debuncher Abort Kicker Requirements							
Integrated field (Kg-m)	Kick angle mrad	Rise time 95%/5% ns	Fall time 95%/5% ns	Flat top ns	Peak rate Hz	Average rate Hz	Duty cycle %
1.81	6.1	1,400	n/a	1,700	7.5	6.0	40

Debuncher Abort Kicker Plan							
Integrated field (Kg-m)	Kick angle mrad	Rise time 95%/5% ns	Fall time 95%/5% ns	Flat top ns	Peak rate Hz	Average rate Hz	Duty cycle %
1.81	6.1	450	500	1,700	7.5	6.0	40

Debuncher Abort: Clean-up Cycle



- Beam leftover after each Debuncher spill cycle needs to be sent to an abort
  1. In a 1.33 second Nova cycle, there are eight iterations of 3.0×10^{12} 8GeV protons being injected into the Debuncher and resonantly extracted to the Mu2e experiment.
  2. It is assumed that 95-98% of the beam will be successfully spilled each cycle
  3. The remaining 2-5% of the beam (5% would be 9.0×10^{11} protons/sec) needs to be sent to a beam abort.

9×10^{11} protons/sec = [(6 Booster batches) x (4×10^{12} protons/pulse) x (0.05)]/1.33 seconds

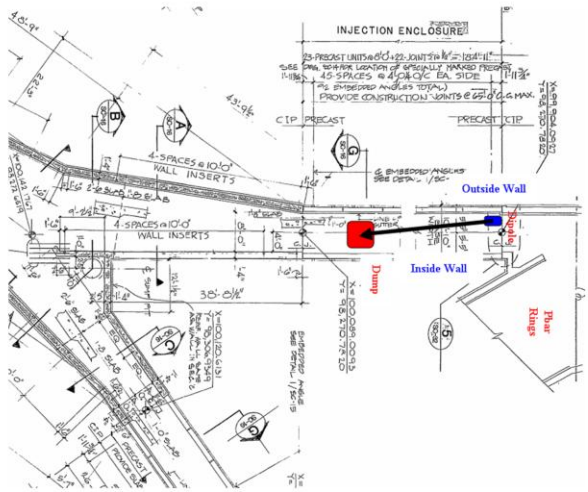
Debuncher Abort: Lost Beam Permit

- We also need to send beam to the Debuncher abort when there is a permit trip.

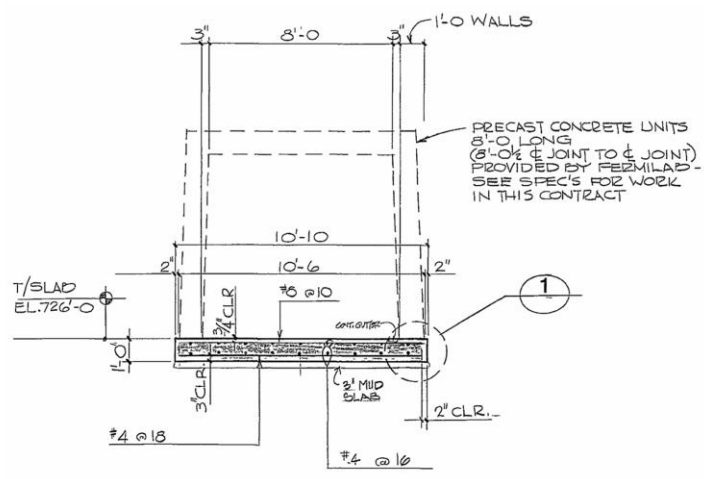
1. There is a finite amount of time needed to reset an abort trip.
2. Experience with Booster and MiniBooNE shows us that we would never expect more than one permit trip per minute.
3. In this case the abort would need to be able to take the entire injected Debuncher beam intensity (3.0×10^{12}).
4. 3.0×10^{12} protons/minute or 5×10^{10} protons/sec.

5×10^{10} protons/sec = (3×10^{12} protons/minute)/(60 sec/min)

Debuncher Abort Location



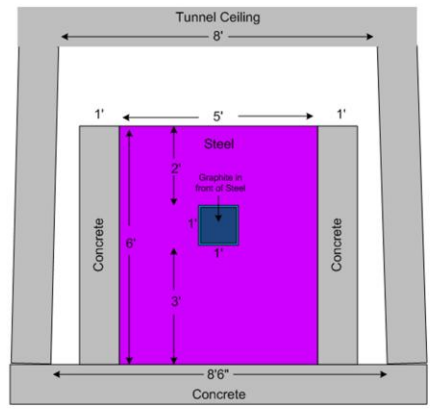
AP-2 Tunnel


3"
8'-0
3"
1'-0 WALLS
PRECAST CONCRETE UNITS
8'-0 LONG
(8'-0" ℄ JOINT TO ℄ JOINT)
PROVIDED BY FERMILAB -
SEE SPEC'S FOR WORK
IN THIS CONTRACT
10'-10
2"
10'-6
2"
T/SLAB
EL.726'-0
#5 @10
1
3/4" CLR
CONT. CENTER
1'-0"
3" CLR.
3' MID SLAB
2" CLR.
#4 @ 18
#4 @ 16

Debuncher Beam Dump in AP2: Initial Design

- Tunnel enclosure is 8'6" wide at floor level and 8' at ceiling level.
- We start with an initial design of a beam dump that is the approximate size of the MI-8 beam dump.
- This fits nicely in the AP-2 line with space on all sides for additional shielding.
- Shielding could be expanded to make a shielding wall and block passageway to transport.
- Gaps may need to be left for cable trays and LCW lines.

Debuncher Beam Abort Cross Section



Steel

332 ft3

81.3 tons

Graphite

50,000 cc

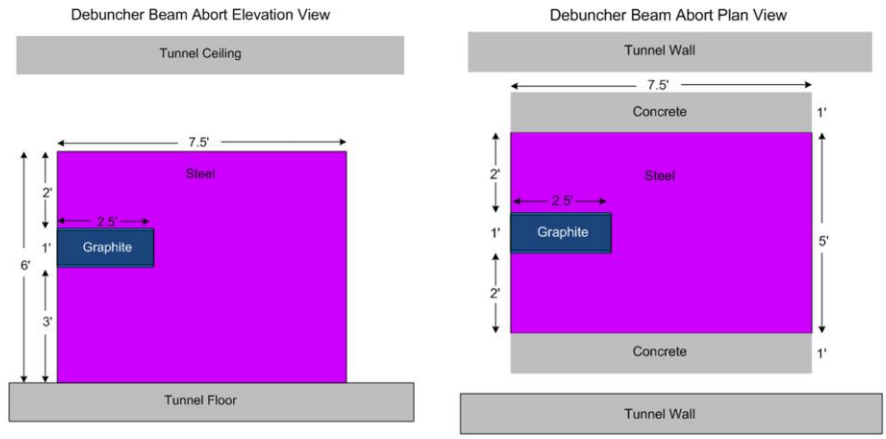
110 Kg

Concrete

305 ft3

44.153 lbs

Debuncher Beam Dump: Initial Design

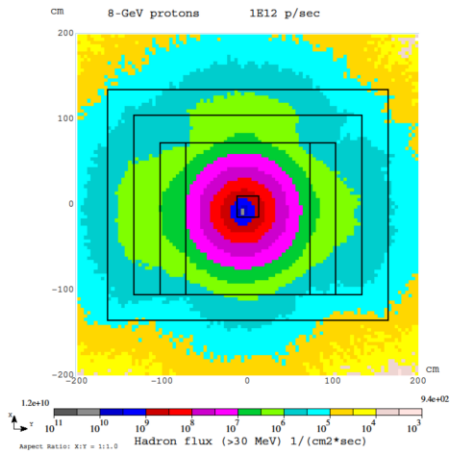


Debuncher Abort Materials

- Steel
  - 332 ft3
  - 81.3 tons
- Graphite
  - 50,000 cc
  - 110 Kg
- Concrete
  - 305 ft3
  - 44.153 lbs

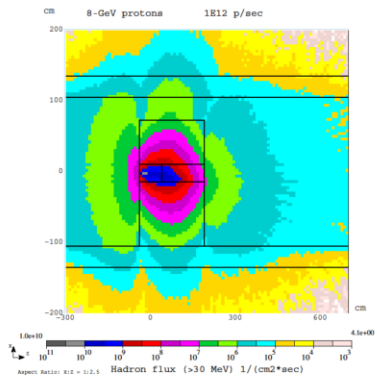
Hadron Flux Cross Section

- MARS run was completed by Igor Rakhno using our model of our beam abort.
- Here we show the hadron flux as viewed in all three planes.

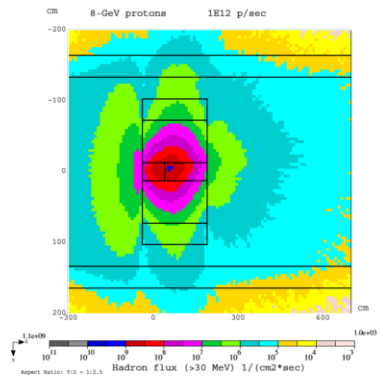


Cross Section

Hadron Flux



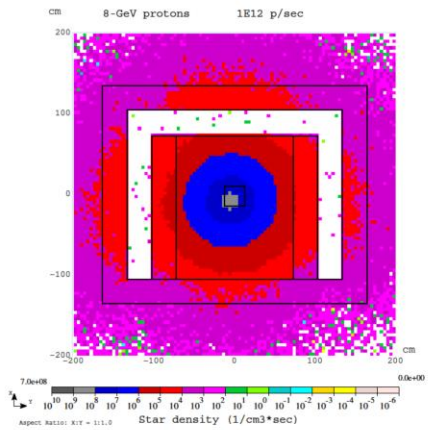
Elevation View



Plan View

Debuncher Abort: MARS Data

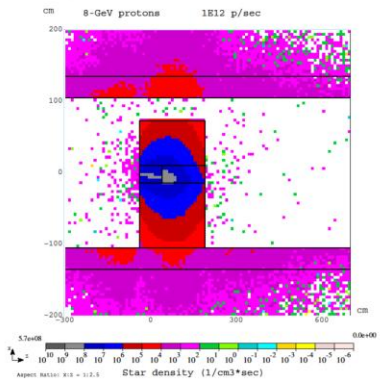
- MARS run was completed by Igor Rakhno using our model of our beam abort.
- Kamran Vaziri completed a surface water and ground water activation analysis.
  - Surface Water
    - Assumed 3.55 x 10^{19} protons/year
    - Conservative estimate of one sump discharge per month
    - Concentration of radioactive contaminants in the sump will be ~3% of the limits for surface water.
  - Ground Water
    - Used the most conservative hydraulic conductivity in the vicinity of the AP-2 line.
    - After five years of operation, the concentration of radionuclides in the ground water will be 0.009% of the limit for ground water.



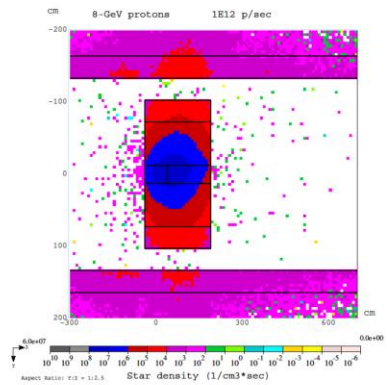
Cross Section

"Star Density" is usually expressed in units of 1/(cm3*sec). It is used to quantify the number of inelastic high-energy interactions (incident protons, pions etc above 50 MeV) with target nuclei that occur in 1 cm3 per 1 second.

Debuncher Abort MARS Data
Star Density

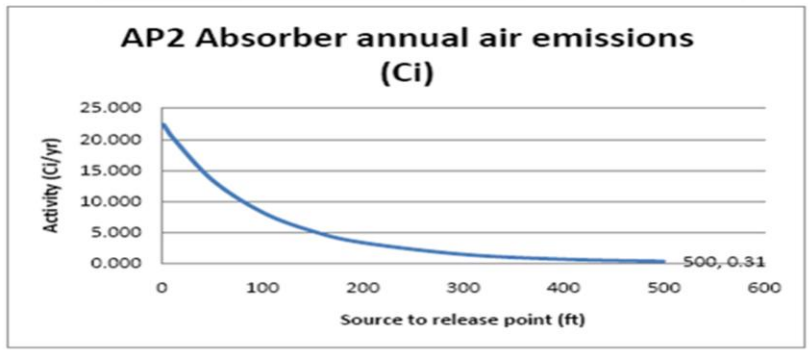


Elevation View



Plan View

Debuncher Abort: Air Activation

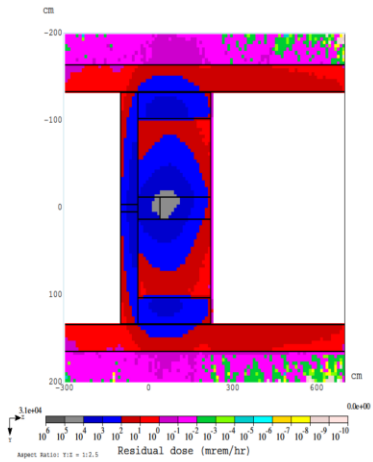


Air activation analysis done by Kamran Vaziri

- Analysis assumes one air exchange per hour.
- Worst case scenario is 22.5 Ci/yr if the air was released from the tunnel at the location of the dump. The 2010 Pbar target numbers were 55 Ci/yr. Mu2e solenoid will be 60 Ci/yr.
- Overall Mu2e airflow design needs to take into account all radiation sources and release points.
- We will revise calculation with more accurate air flow and release point data later on.

Worst case scenario is 22.5 Ci/yr if tunnel release point was at the dump.
Assumes one air exchange per hour
A overall air flow design has yet to be constructed to take into account all radiation sources and release points.
Plans are being considered to slow down the air flow to allow longer decay time and also limiting release points.
2010 Pbar Target was 55 Ci/yr
Mu2e solenoid will be 60 Ci/yr

Debuncher Abort MARS Data Residual Dose

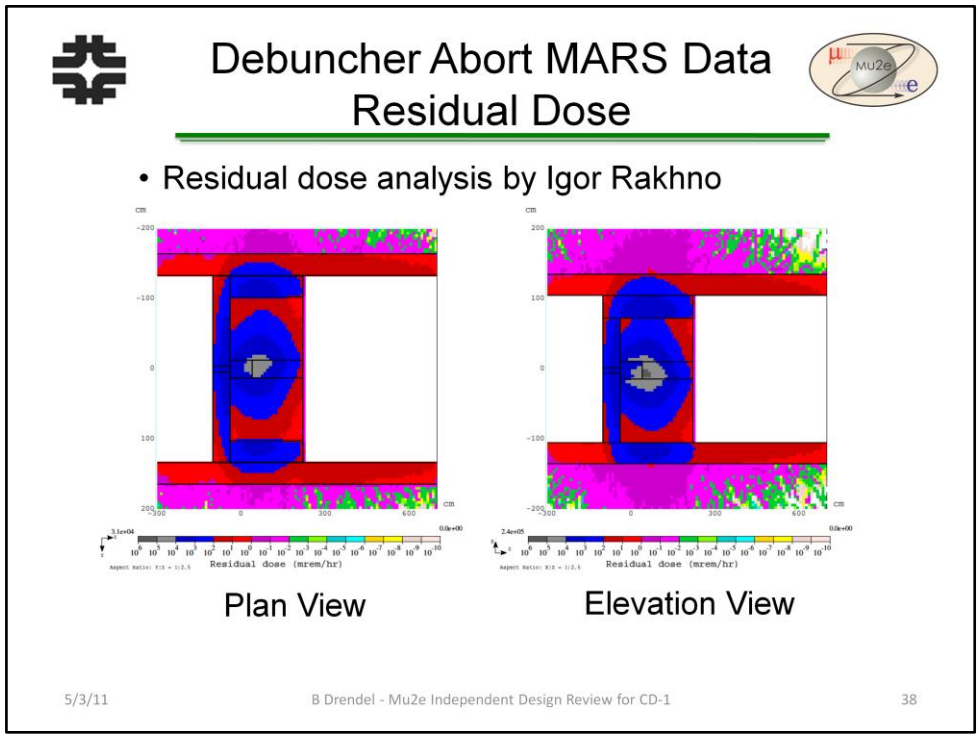


Plan View

Residual dose analysis by Igor Rakhno

- With our original dump design, we ran into a possible issue with residual radiation.
- There is a requirement that the residual dose not exceed 100mrem/hr at 30cm from the activated surface after a 30 day irradiation and a 1-day cool down.
- The original design, rates were calculated at ~1R/hr.
- Modified design:
  - Added 60cm of concrete in front
  - Increased the length of the absorber
  - The cross sectional size of steel increased
  - Concrete added at the top
- The absorber now takes up the entire tunnel enclosure.
- Calculated rate is now 120mrem/hr at the front face of the dump
  - We can either add more shielding or increase the cool down to get the dose rate under 100mrem/hr.
- Calculated rate on back side of dump is less than 100mrem/hr

- With our original dump design, we ran into a possible issue with residual radiation.
- There is a usual requirement that the residual dose not exceed 100mrem/hr at 30cm from the activated surface after a 30 day irradiation and a 1-day cool down.
- The original design, rates were 1R/hr.
- Modified design to add 60cm of concrete in front, increased the length of the absorber, the cross sectional size of steel increased, and concrete added at the top
- The absorber now takes up the entire tunnel enclosure.
- Calculated rate is now 120mrem/hr.



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- Modified design to add 60cm of concrete in front, increased the length of the absorber, the cross sectional size of steel increased, and concrete added at the top
- The absorber now takes up the entire tunnel enclosure.
- Calculated rate is now 120mrem/hr.

Debuncher Abort: Dump Temperature

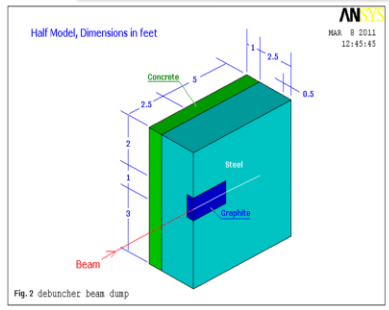


Fig. 2 debuncher beam dump

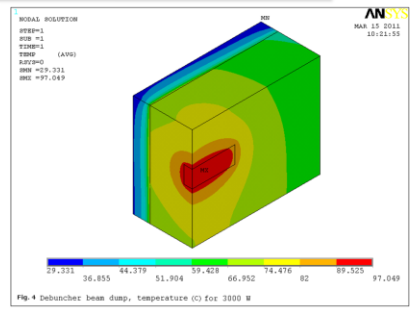


Fig. 4 Debuncher beam dump, temperature (C) for 3000 W

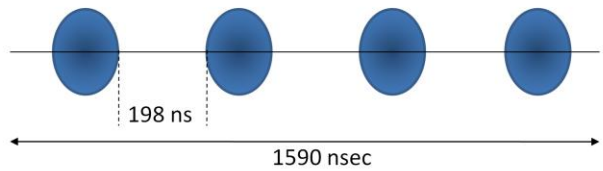
Dump temperature analysis by Zhijing Tang

- The thermal conductivities used in the model are: 100 W/m-K for graphite, 40 W/m-K for steel and 1 W/m-K for concrete.
- Beam heating power of 3000 W was used.
- Heat is uniformly distributed in the graphite core.
- We assume surrounding air temperature is 25 C, and use film coefficient of 5 W/m^2-K for free convection.
- Temperatures is quite low, so no water cooling will be required.

Accumulator Abort

- Supplemental material for the Accumulator abort analysis

Accumulator Abort Kicker



- Bunches will have 198 ns gaps for the kicker to rise and fall through
  - Larger gaps as bunches are removed
- Kicker flat-top needs to cover the entire 1590 ns Accumulator revolution period

Accumulator Abort Kicker Requirements							
Integrated field (Kg-m)	Kick angle mrad	Rise time 95%/5% ns	Fall time 95%/5% ns	Flat top ns	Peak rate Hz	Average rate Hz	Duty cycle %
1.19	4.0	200	200	1,600	1.5	1.5	10

Accumulator Abort Kicker

- Located between A5Q4 and A5B3 in the A50 straight section
- Reuse three AP-4 kicker magnets
- Physical kicker aperture is 42 mm horizontal x 56 mm vertical
- Power supply modeled after NOvA style kicker supply
- A new power supply with the three modules powered in parallel meets the rise time requirement
  - Magnet modules will need to be reconditioned
  - Power supply made up of three new switch tubes, 1 new resonant charger, three new 10 Ω loads, one new control system, one new Fluorinert cooling system

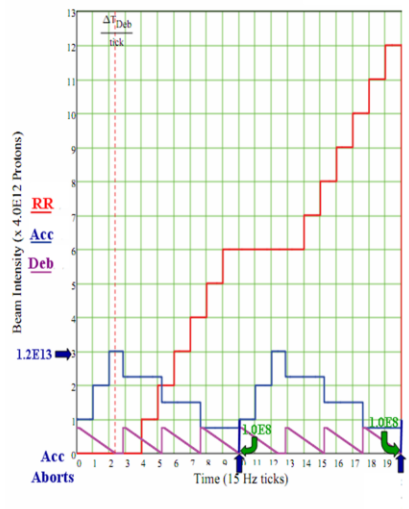
Accumulator Abort Kicker Requirements							
Integrated field (Kg-m)	Kick angle mrad	Rise time 95%/5% ns	Fall time 95%/5% ns	Flat top ns	Peak rate Hz	Average rate Hz	Duty cycle %
1.19	4.0	200	200	1,600	1.5	1.5	10

Accumulator Abort Kicker Plan							
Integrated field (Kg-m)	Kick angle mrad	Rise time 95%/5% ns	Fall time 95%/5% ns	Flat top ns	Peak rate Hz	Average rate Hz	Duty cycle %
1.19	4.0	150	150	1,600	1.5	1.5	10

Accumulator Abort: Clean-up Leftover Beam

Beam leftover after all four Accumulator 2.5MHz bunches are extracted to the Debuncher will need to be sent to an abort

1. The leftover Accumulator beam will be cleaned-up twice every 1.33 second Nova cycle.
2. **Intensity Per Pulse:** Approximately 1.0eE8 8GeV protons will be leftover every pulse.
3. **Average Rate** assuming 75% uptime:
   - **1.13 x 10^8 protons/sec**
   - **9.72 x10^{12} protons/day**
   - **3.55 x 10^{15} protons/year**



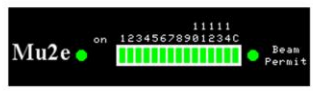
1.13 x10^8 protons/sec = (1.0x10^8 protons/Acc cycle) x (2 Acc cycles/Nova Cycle) x (1 Nova cycle/1.33 sec) x 0.75

9.72 x10^{12} protons/day = (1.13 x10^8 protons/sec) x (86,400 seconds/day)

3.55 x10^{15} protons/year = (9.72 x10^{12} protons/day) x (365 days/year)

Accumulator Abort: Lost Beam Permit

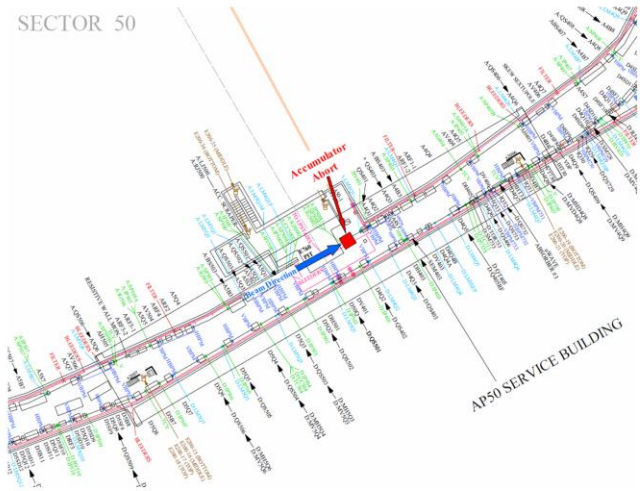
- We also need to send beam to the Accumulator abort when there is a permit trip.



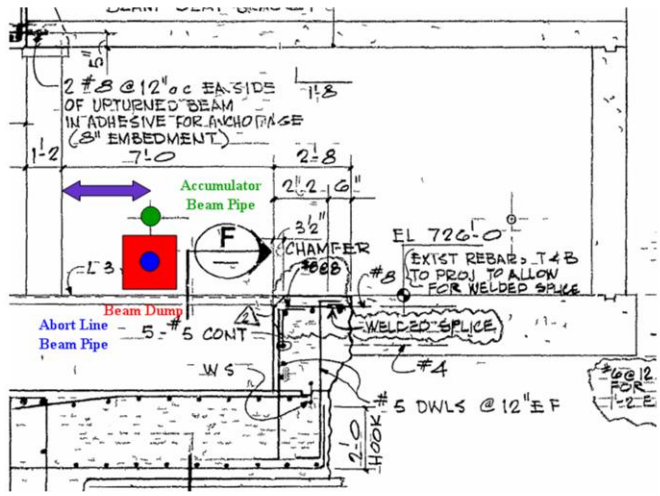
  - Peak Rate: Over short periods the worst case scenario would have the permit dropping once per minute and would need to be able to handle the full intensity of all three booster batches injected.
    - 2 x 10^{11} protons/sec
  - Average Rate: Over the course of a day we would expect permit trips on the order of 10-100 times. For a day with 100 trips with 75% uptime
    - 9.0 x 10^{14} protons/day or 3.29 x 10^{17} protons/year.

Peak Rate: 3 * (4 x 10^{12} protons) / 60 seconds = 2 x 10^{11} protons/sec
Average Rate: 3 * (4 x 10^{12} protons) * 100 * 0.75 = 9.0 x 10^{14} protons/day or 3.29 x 10^{17} protons/year.

Accumulator Abort Location

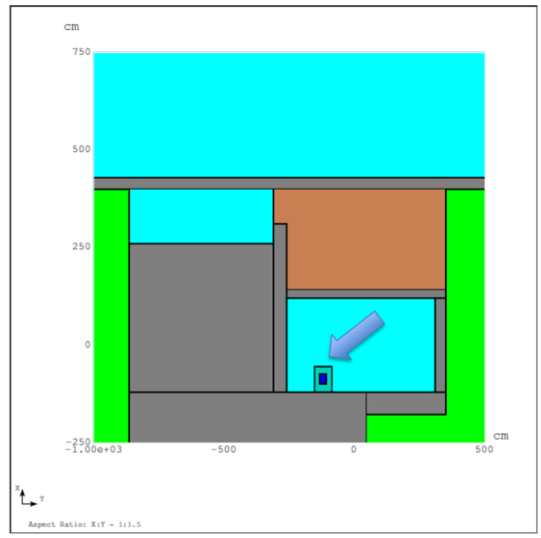


Accumulator Abort Location



Accumulator Abort: Cross Section

- Dump is a graphite core surrounded by iron.
- Dump is 26” tall x 26” wide x 10’ long.
- Core is 10” tall x10” wide by 2.6’ long.
- Drawing from Mars model created by Igor Rakhno.



Steel

44.5 ft3

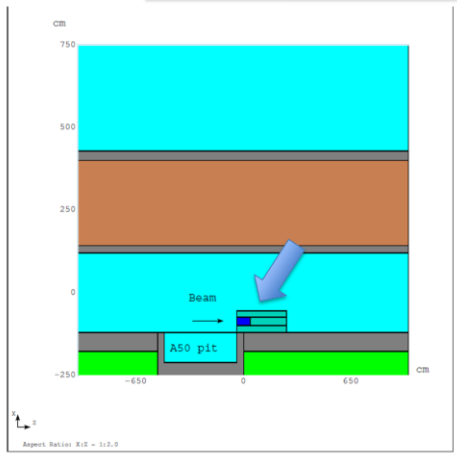
10.9 tons

Graphite

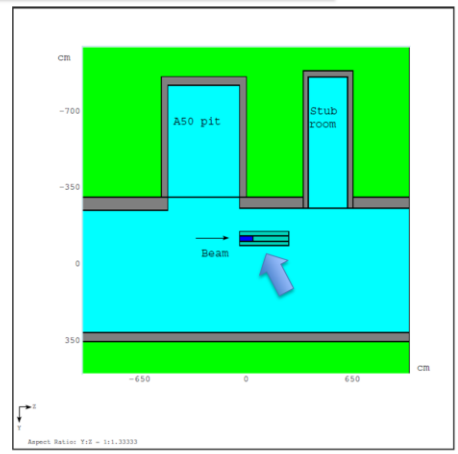
50,000 cc

110 Kg

Accumulator Abort: Elevation and Plan Views



Elevation View

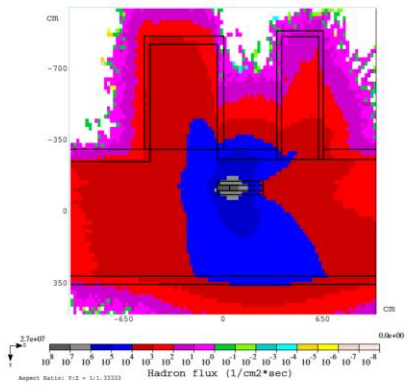


Plan View

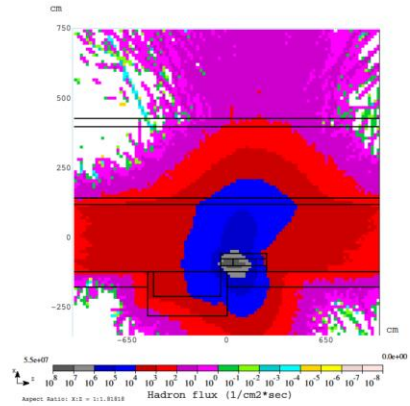
Accumulator Abort Materials

- Steel
  - 44.5 ft3
  - 10.9 tons
- Graphite
  - 50,000 cc
  - 110 Kg

Accumulator Abort MARS Data: Hadron Flux

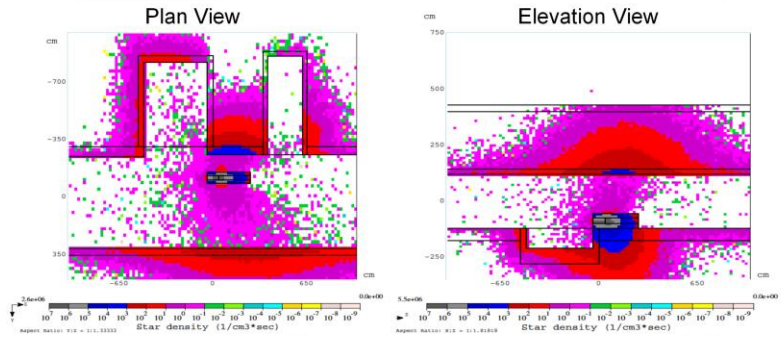


Plan View



Elevation View

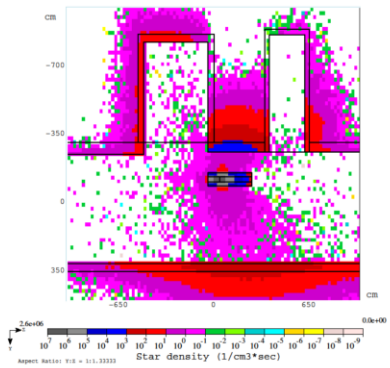
Accumulator Abort MARS Data:



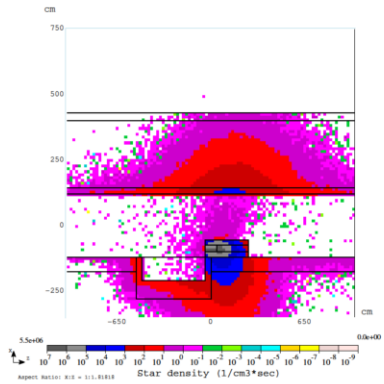
Kamran Vaziri completed a surface water and ground water activation analysis.

- Surface Water
  - Concentration of radioactive contaminants in the sump will by 0.8% of the limits for surface water.
- Ground Water
  - After five years of operation, the concentration of radionuclides in the ground water will be 0.0002% of the limit for ground water.

Accumulator Abort MARS Data: Star Density

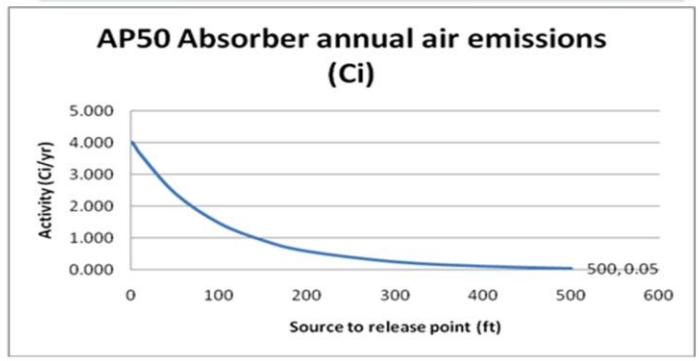


Plan View



Elevation View

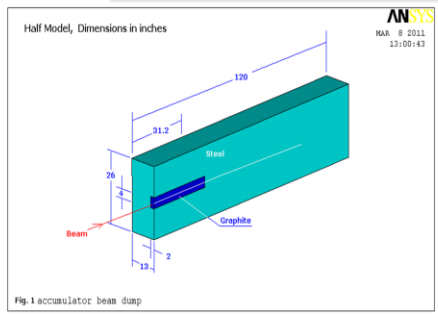
Accumulator Abort: Air Activation

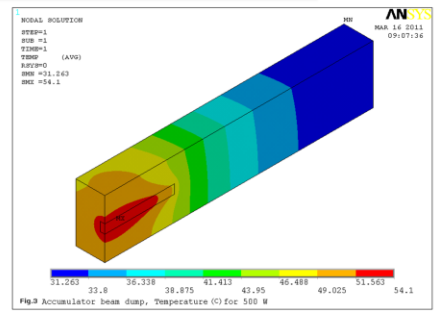


Air activation analysis done by Kamran Vaziri

- Assume one air exchange per hour
- Worst case scenario is about 4 Curies per year, which is about 18% of release from the Debuncher beam dump.

Accumulator Abort: Dump Temperature





Dump temperature analysis by Zhijing Tang

- The thermal conductivities used in the model are: 100 W/m-K for graphite, 40 W/m-K for steel and 1 W/m-K for concrete.
- For beam heating power, we use 500 W.
- Heat is uniformly distributed in the graphite core.
- We assume surrounding air temperature is 25 C, and use film coefficient of 5 W/m^2-K for free convection.
- Temperatures are quite low, so no water cooling is required.

Misc Supplemental Slides

Shared Abort Challenges

- Accumulator Extraction for Abort
  - Accumulator Extraction Kicker
    - Flat is only long enough to extract one of the four 150nsec bunches.
    - Extracting to the abort will require a 1.6 usec flattop to remove the entire circumference of the beam.
    - Having dual PFNs of different lengths on the same kicker was discussed with experts and is believed to not be practical.
  - Accumulator Abort Kicker
    - We would need a separate kicker, but the same septum.
    - A solution to this would be to use the existing A:EKIK tank in the A:IKIK location, modified so that the modules are wired in parallel instead of series.
    - This is a low duty cycle kicker, so the existing electronics and PFNs would be reused.

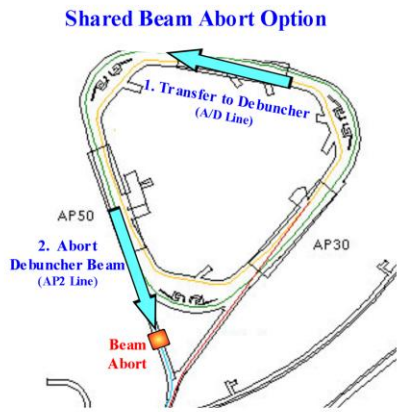
Technical Challenges

- Limited space
  - Abort would need to fit under existing Accumulator beam pipe.
- Competition with space for RF.
  - If the Accumuator RF is located in A50, there will not be enough space to locate the abort line at this location.
  - In this case mirror symmetry of the lattice would allow us to locate the dump in A30.
  - Since there is no pit in that location, the dump would be at floor level and as a result the c-magnet and extra dipole could be eliminated.

Shared Beam Abort Option

In the shared abort option, the Accumulator beam would be transferred to the Accumulator via the A/D line, and then sent to the Debuncher dump.

- Accumulator Extraction kicker flattop time is not long enough.
  - Extraction kicker has a flattop short enough to selectively extract one of the four bunches
  - For the abort, we need to extract the entire circumference.
  - We could use the existing A:EKIK tank in the A:IKIK location, modified so that the modules are wired in parallel instead of series. This would leave us short on spares.
  - Because of the low duty cycle we could also repurpose the existing kicker electronics and PFN's
- Synchronization issues if you want an immediate abort. Power supplies would have to be able to rapidly charge after their normal beam transfer discharges.
- If we could live with losing beam during the cycle and wait to abort the beam until the end of the cycle, then we could synchronize an abort following a permit trip with the normal Debuncher clean-up at the end of the cycle.

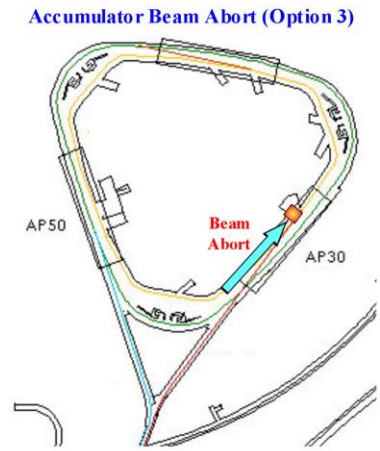


Shared Abort Option Advantages

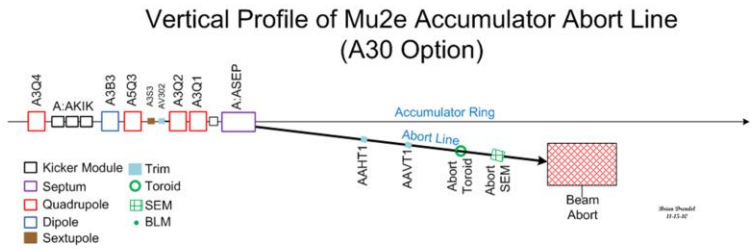
- Sharing a common dump saves the design and building of a second dump.
- The additional beam load due to the Accumulator on the Debuncher dump is small, so the Debuncher dump would not have to be redesigned to handle the extra load.

Accumulator Beam Abort

- Another option is to place a separate Accumulator abort in the A30 straight section.
- This option is very similar to the A50 beam dump option, with the exception that the beam dump would be at floor level instead of below floor level in a pit.



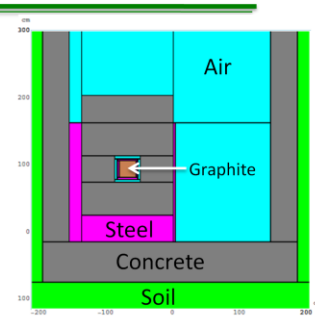
Separate Dump at A30

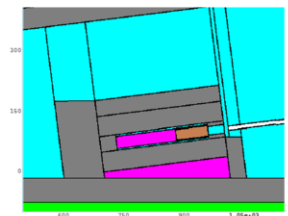


- Three kicker modules located between A3Q4 and A3B3 would provide a 4mr kick downward to the beam.
- Beam enters the field region of a septum downstream of A5Q3
- Beam dump would sit on the floor in the A30 region.
- If the Accumuator RF is located in A30, there will not be enough space to locate the abort line at this location.

Designing the Dump

- We will base the design of our dump on the existing Booster MI-8 Line dump.
- The Booster sits on the floor of the MI-8 enclosure against the tunnel wall.
- It has an outer shell of concrete 54"x54"x122".
- Inside the concrete is a 11.5"x11.5"x58" steel core that is slid into a 1" steel collar.
- In front of the steel core is a 10"x10"x32" graphite block enclosed in a 1" steel jacket. The graphite is used to counteract heating issues.
  - Steel has a melting point of ~1000 °C while graphite has a 3000 to 5000 °C melting point.
  - The Booster dump can run 6E12/pulse at 10Hz for 20 minutes before the steel core runs into melting issues.
  - Booster has 4 thermocouples installed to monitor temperature.
- I. Rakhno (FERMILAB-TM-2340-AD) showed that addition of a minimal amount of shielding to the MI-8 dump increased the allowed beam from 3E18 protons/year to 5E18 protons/year while staying within ground water, surface water and air activation limits.
  - 16" of concrete added at the top
  - 1" steel slab on right
  - 6" steel slab underneath
  - 6" steel slab on left
  - Extra concrete added in front of and behind the dump





Comparing MI-8 and Mu2e Dumps

Specification	MI-8 Dump	Mu2e Debuncher Dump
Peak Beam Intensity (protons/pulse)	$7x10^{12}$	$3x10^{12}$
Maximum Beam Intensity (protons/year)	$6.8x10^{18}$	$2.0x10^{19}$

- Mu2e Dump advantages
  - Moving dump to the center of the enclosure, maximizes the amount of shielding that we can add.
  - Lots of room for additional shielding on all sides of the dump.
  - Could stack shielding from wall to wall and floor to ceiling if necessary.

Beam Permit

Beam Permit

- There will be three beam permits used for Mu2e Operation:
  - AP1/AP3/Accumulator
    - Use existing Pbar permit loop (covers AP1, AP3 & Rings)
    - Single input back to BSSB in MCR
    - C201 (5MHz permit signal) & C479 (monitor clock events) moved from MCR to near kicker at AP50
  - Debuncher
    - New loop
    - Cable pulls AP10, AP30, AP50 and experimental hall.
    - Copper based (go through tunnel)
    - Single input to AP1/AP3/Accumulator permit
    - C201 and C479 cards near kicker at AP50
  - P1/P2
    - P1 and P2 permits combined (since no Tevatron)
    - Single input back to BSSB in MCR

Questions?

- A collection of questions and answers from the talk

Accumulator Abort Rad Levels Kicking through beam

How big is the rad dose rate is if the Accumulator abort kicker rises through up to 1.2E13 of debunched beam?

- Tony Leveling and Jim Morgan radiation shielding measurements for Run II answers this question.
  - One of the measurements was made with 3.6E13 being lost in a single beam pulse on ELAM.
  - This is a pretty good parallel for the abort question, because it is a 2 m long magnet being hit with a similar amount of beam.
  - The single pulse accident condition caused a peak 25 mR/Hr dose rate in AP-30. In the case of Mu2e and the abort, there will be a factor of 3 less beam than our measurement.
  - Also, since the rise time of the kicker is 200 ns, there will also be another factor of 8 reduction because only 1/8 of the beam is seeing a partial kick.
  - So, there is a factor of 24 reduction without taking into account that the beam won't all hit one magnet, it will be sprayed over a larger area. So the dose will only be about 1 mR/Hr, small potatoes compared to other rad issues.